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HARD GAMMA-RAY EMISSION FROM BLAZARS

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Abstract

The γ-ray emission expected from compact extragalactic sources of nonthermal radiation is examined. The highly variable objects in this class should produce copious amounts of self-Compton γ-rays in the compact relativistic jet. This is shown to be a likely interpretation of the hard γ-ray emission recently detected from the quasar 3C 279 during a period of strong nonthermal flaring at lower frequencies. Ways of discriminating between the self-Compton model and other possible γ-ray emission mechanisms are discussed.

1. INTRODUCTION

The high flux of γ-rays recently observed toward the quasar 3C 279 (Hartman *et al.*, these proceedings) came as no surprise to astrophysicists who study nonthermal radiation from compact extragalactic radio sources. Highly variable nonthermal extragalactic sources (blazars) should, at least in theory, be strong hard γ-ray emitters.

At radio to infrared, and often optical, frequencies, the emission from blazars is almost surely incoherent synchrotron radiation. The evidence for this lies in the characteristic polarization properties – modest linear polarization and very small circular polarization – as well as the measured brightness temperatures, which lie in the few$\times 10^{11}$ K range expected for incoherent synchrotron emitters (see, e.g., Jones, O'Dell, & Stein 1974). In the most compact regions of the source, the synchrotron photon density is quite high, and therefore inverse Compton scattering of the synchrotron photons off the relativistic electrons – "self-Compton" emission – is expected to be important. In fact, if upper limits to the size of the source are derived from timescales of brightness variability, the photon densities would be so high that most of the luminosity should emerge in the X-ray and γ-ray regions of the spectrum (e.g., Burbidge, Jones, & O'Dell 1974; Marscher *et al.* 1979). In a few well observed cases, this over-prediction of high-energy emission is substantiated by actual measurements of the photon density (e.g., Marscher & Broderick 1985; Unwin *et al.* 1985). The most likely resolution of this discrepancy is that the emission regions in such sources are moving at relativistic speeds almost directly toward us, which also provides an explanation for the faster-than-light ("superluminal") apparent motions found in the compact jets of such sources (see Marscher 1987 for a review).

For a well-observed source, the major uncertainty in the self-Compton calculation is the precise value of relativistic beaming (Doppler) factor $\delta \equiv [\Gamma(1-\beta\cos\phi)]^{-1}$, where the bulk velocity of the emitting plasma is βc directed at an angle ϕ to the line of sight, and $\Gamma \equiv (1-\beta^2)^{-1/2}$ is the bulk Lorentz factor. The higher the beaming factor is, the lower is the photon density needed to account for a given observed nonthermal flux from the source. The superluminal apparent speed is given by $\beta_{\rm app} = \frac{\beta\sin\phi}{1-\beta\cos\phi}$, which is a maximum of $\beta_{\text{app}} = \Gamma$ at $\phi = \sin^{-1}(1/\Gamma)$. Observation of the apparent superluminal motion therefore constrains both Γ and ϕ, but does not uniquely determine them. The Doppler factor also causes a time contraction in the observer's frame relative to the rest frame of the emitting plasma. A source that varies by a large factor on a timescale t_{var} therefore can be as large as $\sim ct_{\text{var}}\delta/(1+z)$, where z is the redshift of the entire object.

The fact that COS B did not detect lots of blazars indicates that the Doppler factors are in general high enough so as to allow the photon density in the rest frame of the emitting plasma to be sufficiently low for the self-Compton process to be only a modest source of high-energy photons most of the time. Whether the EGRET and COMPTEL detectors will be sensitive enough to detect this "quiescent" γ-ray emission from any blazars remains to be seen. However, during the major synchrotron flares that are observed in most blazars from radio to infrared (and often visual) frequencies, the synchrotron photon density should increase to a level sufficient to cause a major flare in self-Compton X-rays and γ-rays.

In what follows, we discuss the expected spectrum and other observational signatures of a self-Compton flare, with application to the EGRET detection of 3C 279 in June 1991. We then review briefly various other models that could possibly produce hard γ-ray emission from blazars, and show how future observations are potentially capable of discriminating among these possibilities.

2. SELF-COMPTON EMISSION FROM BLAZARS

Bloom and Marscher (these proceedings) give the formulae for first and second order self-Compton emission from a compact nonthermal source. In Figure 1 we display the numerically calculated synchrotron and self-Compton spectrum of a model compact nonthermal source that is meant to approximate very roughly the observed characteristics of 3C 279 in summer 1991, which was a time of flaring at submillimeter wavelengths (Robson 1991) similar to that which occurred during the pronounced X-ray flare of 1988 (Makino *et al.* 1989). The slope of the νF_ν vs. ν spectrum is given as a function of frequency in the bottom panel of Figure 1. For the particular model spectrum shown, first order scattering dominates over second order, which is suppressed owing to the Klein-Nishina limit. Although we have not exhausted all parameter space, it appears difficult to reproduce the γ-ray emission of 3C 279 in June 1991 by second order scattering using a simple self-Compton model because of the Klein-Nishina suppression.

The general characteristics of the synchrotron spectrum are: a low-frequency ($\nu < \nu_{\text{m}}$) drop-off owing to synchrotron self-absorption; a high-frequency ($\nu \gtrsim \nu_{\text{u}}^{\text{S}}$) cut-off corresponding to the synchrotron critical frequency of the highest energy electrons; and a power-law of slope $-\alpha = -(p-1)/2$ at intermediate frequencies, where p is the slope of the presumed power-law energy distribution of the relativistic electrons. The first-order self-Compton spectrum, for which the scattering is almost surely completely within the Thomson limit, is a spread-out version of the synchrotron spectrum, with low-frequency fall-off below $\nu_\ell^{1\text{C}} \sim \gamma_\ell^2 \nu_{\text{m}}$ and high-frequency drop-off above $\nu_{\text{u}}^{1\text{C}} \sim \gamma_{\text{u}}^2 \nu_{\text{u}}^{\text{S}}$. Here, γ_ℓ and γ_{u} are the lower and upper Lorentz factor limits of the relativistic electron energy distribution. In between $\nu_\ell^{1\text{C}}$ and $\nu_{\text{u}}^{1\text{C}}$, the spectrum is roughly a power law with the same slope as for the synchrotron spectrum. Note, however, that there is significant curvature to the

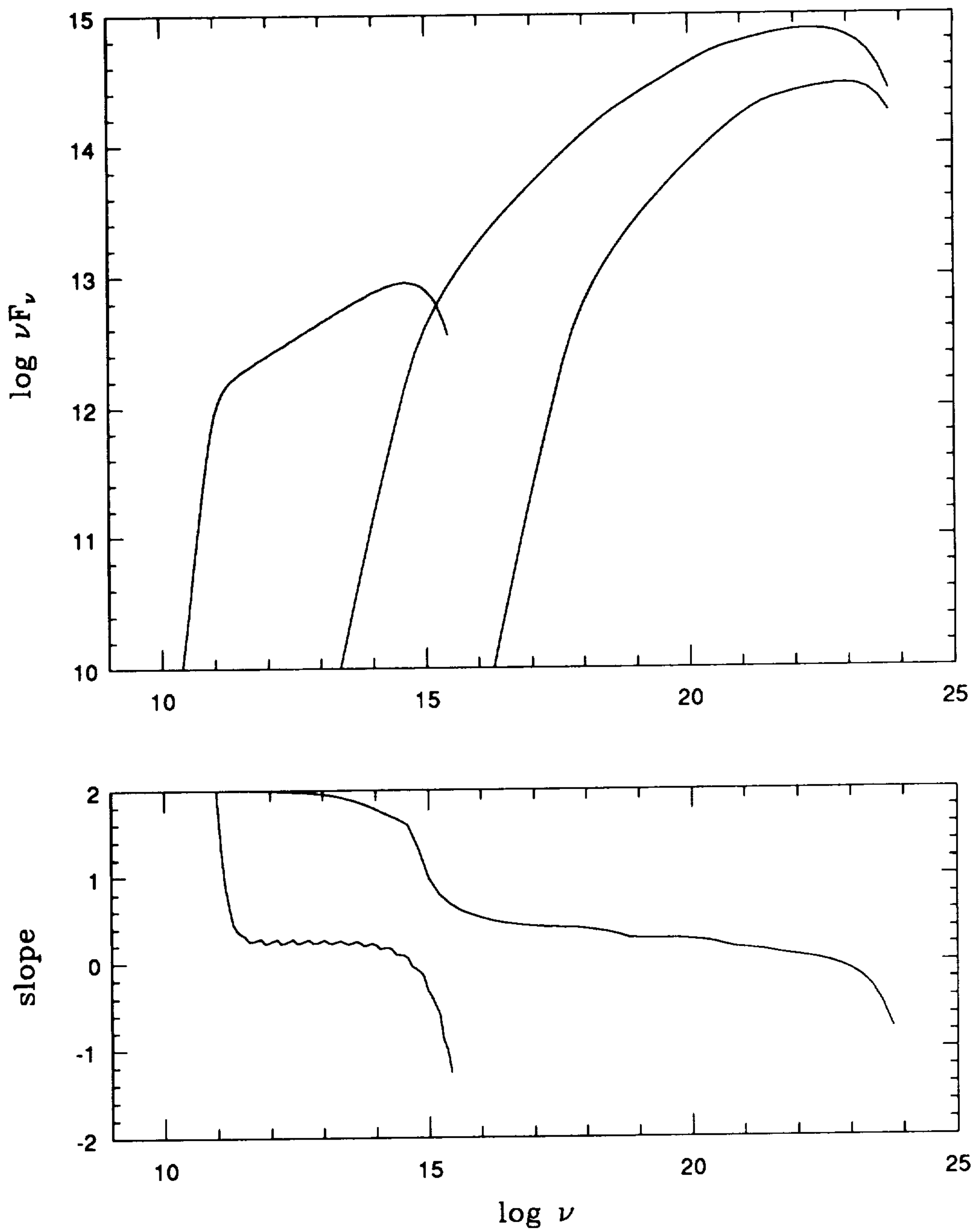

Figure 1 νF_ν spectrum of the synchrotron (left-most curve), first order self-Compton (middle curve), and second order self-Compton (right-most curve) emission from a spherical, uniform, nonthermal source whose overall spectrum is similar to that of 3C 279 in June 1991. The lower panel gives the slope of the νF_ν synchrotron (left-hand) and first + second order self-Compton (right-hand) spectrum as a function of frequency.

self-Compton spectrum unless there are several decades between both the upper and lower synchrotron spectral cut-offs and the upper and lower electron energy cut-offs. In addition, the self-Compton high and low frequency cut-offs are not as sharp as is the case for the synchrotron spectrum.

The character of the second order self-Compton spectrum depends on the values of γ_ℓ, γ_u, ν_m, and ν_u^S. Since the scattered photon (with initial photon energy less than $m_e c^2$) cannot have greater energy than that of the incoming electron, the upper frequency cut-off is $\nu_u^{2C} \sim \gamma_u m_e c^2/h$, where h is Planck's constant. As is seen in Figure 1, this Klein-Nishina cut-off significantly suppresses the second order self-Compton γ-ray luminosity.

The self-Compton X-ray and γ-ray luminosity can be considerably higher than that of the synchrotron emission. [As has been pointed out by R. Blandford (1991), above some high luminosity ratio one must consider quantum effects leading to induced Compton scattering.] The conditions under which this occurs correspond precisely to those that would cause a substantial synchrotron flare, since the ratio of first order self-Compton to synchrotron flux increases as the synchrotron brightness temperature raised to the $(3+2\alpha)$ power (Marscher 1987). (The brightness temperature is proportional to the flux density divided by the square of the angular size.) The self-Compton process therefore acts as an amplifier of the synchrotron fluctuations.

The synchrotron spectrum of 3C 279 is described by a power law of spectral index $\alpha \approx 0.6$ between about 10^{11} Hz and 10^{14} Hz, above which it steepens (Robson 1991). Without contemporaneous VLBI observations at 90 GHz, we cannot determine the angular size of the variable component, and therefore cannot derive the magnetic field strength. If we assume that the magnetic field in the core is of order 0.1 gauss, which is near the value derived for 3C 273 (Marscher & Gear 1985), then the upper electron Lorentz factor cut-off is $\gamma_u \sim 10^4$. The high-frequency drop-off of the first order self-Compton emission then occurs at $\nu \gtrsim \nu_u^{1C} \sim \gamma_u^2 \nu_u^S \sim 10^{22}$ Hz, or about 40 MeV. The spectrum of γ-rays detected by EGRET should then be somewhat steeper than the expected X-ray value of about -0.6. (Note: this is the so-called "energy index" as opposed to the "photon index.") If the hard γ-rays from 3C 279 are from second order self-Compton, the spectrum gradually steepens with frequency (see Fig. 1).

Discerning between a first and second order origin for the hard γ-rays only requires contemporaneous submillimeter or infrared, X-ray, and γ-ray observations. For second order self-Compton, the ratio of hard γ-ray to X-ray flux density $(F_{\nu,\gamma}/F_{\nu,X})(\nu_\gamma/\nu_X)^\alpha$ (corrected for Klein-Nishina suppression) should equal the ratio of X-ray to synchrotron luminosity $(F_{\nu,X}/F_{\nu,IR})(\nu_X/\nu_{IR})^\alpha$ (Jones 1979; Bloom and Marscher, these proceedings).

A more detailed analysis of the γ-ray emission from 3C 279 must include the as yet unpublished contemporaneous radio VLBI, submillimeter–infrared, and (if any) X-ray observations.

3. OTHER γ-RAY EMISSION MECHANISMS

Although one can imagine (and a number of authors have) that copious γ-ray production might occur close to the central engine of an active nucleus, any hard γ-rays thus produced will almost surely be destroyed by pair production off the observed strong X-ray radiation field (McBreen 1979). Since the only two confirmed identification of quasars with hard γ-ray sources are the superluminal sources 3C 273 (Swanenburg *et al.* 1978) and

3C 279 (Hartman *et al.*, these proceedings), it is reasonable to assume for the time being that the γ-ray production arises from the relativistic jets in these objects. A self-Compton origin of the γ-rays from 3C 273 is possible despite the steep slope measured by COS B (Bignami *et al.* 1981), since steep spectra are in fact produced at the high frequency end of the scattered spectrum (see Fig. 1). As is discussed in Marscher and Gear (1985) and Marscher, Gear, & Travis (1992), the observed rapid variability in the X-ray flux of 3C 273 does not necessarily imply that the X-rays are produced close to the central engine: fluctuations in the relativistic jet are capable of producing surprisingly short timescales of variability, especially at high frequencies.

Other processes besides self-Compton emission have been proposed for producing hard γ-rays from blazars. Begelman and Sikora (1987) and Melia and Königl (1989) show that, if the jet originates closer to the central engine than the smallest observed radio component ($\sim$ 1 pc), Compton scattering ("reflection") of the X-rays emitted from an assumed accretion disk will generate a high flux of X-rays and γ-rays. Dermer, Schlickeiser, and Mastichiadis (these proceedings) propose that this process will occur even at the distance of the radio jet. Eichler and Wiita (1978), Giovanoni and Kazanas (1990), and Mastichiadis and Protheroe (1990) have proposed that much of the energy from the central engine is released in the form of high-energy neutrons generated in collisions of relativistic protons. Neutrons with Lorentz factors $\gtrsim 10^5$ would decay about 1 pc from the central engine, thereby injecting relativistic electrons into the radio jet at this distance. γ-rays from the proton-proton collisions could be beamed from the vicinity of the central engine, possibly avoiding complete depletion from pair production. The secondary electrons are also free to engage in self-Compton emission in the radio jet. For the 3C 273 jet, it has been proposed (Bignami *et al.* 1981; Morrison, Roberts, & Sadun 1984) that the γ-rays could be produced through inverse Compton scattering in the extended jet.

In principle, multifrequency observations of variability of the emission from a blazar can discriminate among these disparate models. In the case of self-Compton models, the high-energy emission should amplify the variations of the underlying synchrotron source. The high-energy variations should therefore be simultaneous with the synchrotron variations. It is important to note that this is only true for the *optically thin* synchrotron variations, i.e., those occurring at frequencies higher than the self-absorption turnover frequency $\nu_{\rm m}$. Since $\nu_{\rm m}$ typically lies above $\sim 10^{11}$ Hz, the high-energy fluctuations must be compared with those observed in the submillimeter-wave to infrared part of the spectrum. The radio variations are often time delayed until the variable component expands sufficiently to lower the optical depth to a value $\lesssim 1$. Also, since the high-energy emission is subject to rapid fluctuations on top of major flares (Marscher *et al.* 1992), one should not make too much of short timescale high-energy variations with amplitudes of a few tens of percent that are not coincident with similar infrared fluctuations.

Inverse Compton reflection of uv or X-ray photons from an accretion disk (or other region close to the central engine) off the electrons in a relativistic beam (precursor of the observed radio jet) could have two different signatures. If the incident photon flux varies, one should observe an X-ray or uv flare followed by a time-delayed γ-ray flare, although the time delay would probably be quite short ($\sim$ days). If the flare is caused by an increase in the number of relativistic electrons injected into the beam, the source could be steady in the soft X-ray and uv while a γ-ray flare is observed, followed by a submillimeter-infrared flare that could be time-delayed by weeks or months.

If the γ-rays are produced in proton-proton collisions near the central engine, one would expect the γ-ray flares to precede synchrotron flares, again by weeks or months unless the jet points directly at us. Also, the luminosity in γ-rays should be roughly proportional to the synchrotron luminosity in radio-loud active galaxies (cf. Giovanoni & Kazanas 1990).

Finally, if the γ-rays result from inverse Compton scattering in the extended radio jet, no variability should be seen on timescales of years.

4. WHAT WE CAN LEARN FROM SELF-COMPTON γ-RAYS

If, as seems likely, the hard γ-rays from 3C 279 are of self-Compton origin, contemporaneous radio, submillimeter, infrared, optical, X-ray, and γ-ray observations can nail down many of the physical parameters of the source. As is discussed by Bloom and Marscher (these proceedings), the first and second order self-Compton fluxes depend on the Doppler beaming factor δ and the observed parameters (flux density, angular size, self-absorption turnover frequency) raised to very high powers. This works against obtaining a precise prediction of the high-energy self-Compton flux through observations of the synchrotron source. However, once the self-Compton X-ray and γ-ray fluxes are observed, the parameters of the source are extremely well determined since they depend on the high-energy fluxes raised to very low powers. For a source with $\alpha = 0.6$, one obtains (cf. the relations given by Bloom and Marscher)

$$\delta \propto (F_\nu^{1C})^{-0.19} F_{\rm m} \nu_{\rm m}^{-1.3} \theta^{-1.6}. \tag{1}$$

Here, $F_{\rm m}$ is the synchrotron flux density at the self-absorption turnover frequency $\nu_{\rm m}$, and θ is the angular size of the emitting region. The angular size is not easy to measure, since the most compact radio components are unresolved, even with VLBI, in the majority of sources. The other parameters can, however, be measured rather accurately. Using the second order self-Compton flux, we can derive a second relation:

$$\delta \propto (F_\nu^{2C})^{-0.10} F_{\rm m}^{0.90} \nu_{\rm m}^{-1.4} \theta^{-1.6}. \tag{2}$$

Unfortunately, the Doppler beaming factor depends on angular size in precisely the same way in the two expressions (which is why the γ-ray flux can be predicted from the ratio of X-ray to infrared flux densities). The two expressions at least provide a consistency check on the assumption that the self-Compton process is the mechanism that generates the γ-rays.

Expressions (1) and (2) can therefore be used to determine the value of the Doppler beaming factor δ to within the accuracy of measuring the angular size θ. Notice that, since at least an upper limit to θ can be measured, at least a lower limit to δ can be calculated. Also notice that this procedure is completely independent of the distance scale. However, the apparent superluminal motion of a source is dependent on the distance scale: $\beta_{\rm app} \propto \mu d$, where μ is the proper motion of the superluminal component and d is the distance, which depends on both Hubble's constant H_0 and the deceleration parameter q_0. Once VLBI at millimeter wavelengths becomes commonplace (it can now be done on a limited basis), the values of (rather than upper limits to) θ will be able to be measured for many sources. This, plus observations of the superluminal motion and adoption of particular values of q_0 (necessary for higher redshift objects only) and H_0, will be sufficient to determine both the Lorentz factor and Doppler beaming factor of the variable emission regions in the jet. Given a sufficient number of sources for which this procedure can be carried out, it could even be possible to determine the values of q_0 and H_0 themselves from the expected statistical distribution of orientation angle ϕ (see Marscher and Broderick 1982).

If the hard γ-rays from 3C 279 arise from the self-Compton process within the relativistic jet, the actual luminosity is $L_\gamma \approx 10^{48}\delta^{-4}$ erg s^{-1}. Two factors of δ correspond to beaming within an aberrated angle of δ^{-1}, another factor comes from time contraction (blueshift) for a variable component, and the last factor is the frequency boost (the photons are δ times more energetic in the observer's frame than in the source's rest frame). The apparent superluminal speed, for $q_0 = 0.5$ and $H_0 = 100h$ km s^{-1} Mpc^{-1}, is $\beta_{\rm app} = 2.2h^{-1}$ as determined over the period 1981–1986 by Unwin *et al.* (1989), and about 4 times this value between 1970 and 1972 as determined by Cotton *et al.* (1979). The earlier value results from very limited data by current standards and is based on very simple source models, while the later observations show the source structure to be fairly complex much of the time. On the other hand, the model fitting of Hughes, Aller, and Aller (1991) to the radio flux density and polarization variations implies that the time sampling of the Unwin *et al.* observations is too sparse to identify individual components accurately as they change position on the multi-epoch images. These authors suggest a value of $\beta_{\rm app}$ at least twice that of Unwin *et al.*, but not as high as that of Cotton *et al.* The more frequent monitoring that will be available with the VLBA (to be completed in early 1993) should resolve the issue. Note that δ can be considerably greater than $\beta_{\rm app}$ if the beaming angle $\phi < \sin^{-1}\phi$. From the above considerations, the actual γ-ray luminosity of 3C 279 is likely to be $\lesssim 10^{46}$ erg s^{-1}.

5. CONCLUSIONS

It appears highly likely that the hard γ-rays detected by EGRET toward the blazar 3C 279 in June 1991 were generated by the self-Compton process within the compact relativistic jet apparent on radio VLBI images. Multifrequency monitoring (at least once every few months) of 3C 279 and other similar sources will provide excellent tests of the self-Compton and other emission processes. It is especially important that the observations of the synchrotron emission include both multifrequency radio VLBI and total flux density observations at radio, submillimeter, and infrared wavelengths.

At least one other source, the quasar 4C 39.25, is undergoing a prolonged synchrotron flare of roughly equal amplitude to that of 3C 279 (Marscher *et al* 1991). In addition, the quasar NRAO 140, with high X-ray to radio flux ratio, is also flaring in the radio (Aller and Aller 1991). Both these objects are excellent candidates for detection by EGRET and possibly COMPTEL. We are currently engaged in a project to measure the multifrequency properties of a sample of 31 radio-loud quasars (including the two mentioned above) under the CGRO Guest Investigator Program using the COMPTEL and EGRET sky surveys. We will propose to make repeated pointed observations of those sources from our sample that are detected by CGRO. The scientific return from such studies should be very high.

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